The Lead-Cooled Fast Reactor: Concepts for Small and Medium Sized Reactors for International Deployment

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Background and Motivation

- Many new developments (and much excitement) in nuclear energy technology
- Renewed focus on near-term revitalization of global nuclear industry (Generation III/III+)
- Advanced reactor development in some disarray: Generation-IV (Gen-IV); Global Nuclear Energy Partnership (GNEP)
- Current domestic focus is on high temperature gas reactors and sodium-cooled fast actinide burners
- Some consensus (though misaligned with programmatic developments) on the need for small exportable reactors and fast systems for nuclear material management

Today we consider lead-cooled small and medium sized reactors for international deployment

Both the former GNEP and Gen IV programs considered internationally deployable systems

- **An essential part of GNEP was the design and deployment of exportable, proliferation-resistant reactor technology**

- **Various terms used:**
  - **Small Reactors**
  - **Grid Appropriate Reactors**
  - **Exportable Reactors**
  - **Appropriately-sized Reactors**

- **The history of seeking such solutions goes back at least 10 years**

Today's presentation addresses past history and current status of two lead-cooled systems for international deployment: SSTAR and ELSY

Overview of Lead-cooled Fast Reactor (LFR) Technology

- **The LFR offers a reactor technology option characterized by a fast neutron spectrum; a liquid coolant with a very high margin to boiling and benign interaction with air or water; and several features that lend it simplicity and robustness.**

- **Two design thrusts are being considered:**
  - **A small, transportable system of 10–100 MWe size that features a very long refueling interval. (SSTAR)**
  - **A larger system rated at about 600 MWe, intended for central station power generation and waste transmutation. (ELSY)**

- **LFR concepts offer substantial benefits in terms of economic performance, safety, simplification and proliferation resistance.**

Some chemical and thermal characteristics of liquid metal coolants

Coolant	Melting Point (° C)	Boiling Point (° C)	Chemical Reactivity (w/Air and Water)
Lead-Bismuth (Pb-Bi)	125	1670	Inert
Lead (Pb)	327	1737	Inert
Sodium (Na)	98	883	Highly reactive

Lead and Lead-Bismuth Coolants Provide Promising Overall Characteristics Although Sodium Coolant Technology is More Highly Developed

Some Nuclear Characteristics of Liquid Metal Coolants (from Todreas, 2004)

	Atomic mass (g/mol)	Relative moderating power	1MeV Neutron absorption cross section (mbarn)	1MeV Neutron scattering cross section (barn)
Lead (Pb)	207	1	6.001	6.4
LBE (Pb-Bi)	208	0.82	1.492	6.9
Sodium (Na)	23	1.80	.230	3.2

On balance, heavy metal coolants enable a hard energy spectrum and a good neutron economy, important for actinide burning

International Activities in Lead/Lead Bismuth Reactor Research

Russia - Mid 1960's to present

- 7 “Alpha Class” Submarines (~73-155 MWe) (See Movie)
- 12 reactors including 2 on shore prototypes
- 80 reactor-years experience
- Accelerator Driven Subcritical (ADS) reactors
- Reactor systems (BREST; SVBR-75/100)
- Collaborating with Europeans on ELSY

Europe and Asia - 2000 to present

- Numerous experimental test loops using Lead and Pb-Bi
- Toshiba concept of a Pb-Bi cooled 4-S reactor
- Korean design work
- Ongoing ADS systems in Europe and Asia
- European Lead-cooled System (ELSY)

U.S. Programs - 1997 to present

- Los Alamos National Laboratory - Delta Loop for corrosion testing
- University of Nevada at Las Vegas - Lead-Bismuth Loop
- MIT - alloy studies to mitigate corrosion
- UC-B Encapsulated Nuclear Heat Source (ENHS) and related studies
- Small, Secure Transportable Autonomous Reactor (STAR-SSTAR)

U.S. LFR program

U.S. Programs - 1997 to present

- **LLNL studies resulted in IAEA presentation on long-life reactors with no on-site fuel storage**
- **DOE sponsored research initiative funded STAR-LM (Argonne Lab), STAR-LW (IRIS@Westinghouse), ENHS (UC-B) and several other projects**
- **LLNL/UCB/ANL interactions on the Japanese 4-S reactor concept**
- **US Gen-IV program adopted the small LFR (10-100MWe) as one of its concepts; LLNL/ANL/LANL/UC - STAR and SSTAR projects are continuing**
- **A new international (Gen-IV International Forum, GIF) LFR research plan for SSTAR and the European Lead-cooled System (ELSY)**

The GIF-LFR System Research Plan

- The Generation-IV International Forum (GIF) provides a means for international coordination of advanced reactor research

- The GIF-LFR Steering committee has operated since 2004

Generation IV Nuclear Energy Systems

System Research Plan for the Lead-cooled Fast Reactor (LFR)

Final Draft, 4 April 2008

NOTE: DRAFT SYSTEM RESEARCH PLAN (SRP) FOR THE LEAD-COOLED FAST REACTOR (LFR).

It has been assembled by the LFR Provisional System Steering Committee (PSSC) following formal committee meetings and informal working sessions. It should be considered a work-in-progress. It is being made available outside the PSSC for review and feedback. Note that the section on fuels draws from the parallel efforts of the SFR-SSC. Comments and feedback will be welcome. Reviewers should note the following key features of the proposed plan: (1) the plan takes a dual track (with a small transportable system and a moderate or large central station system); and (2) the plan suggests a single demonstration facility to serve both tracks.

Preparing Today for Tomorrow's Energy Needs

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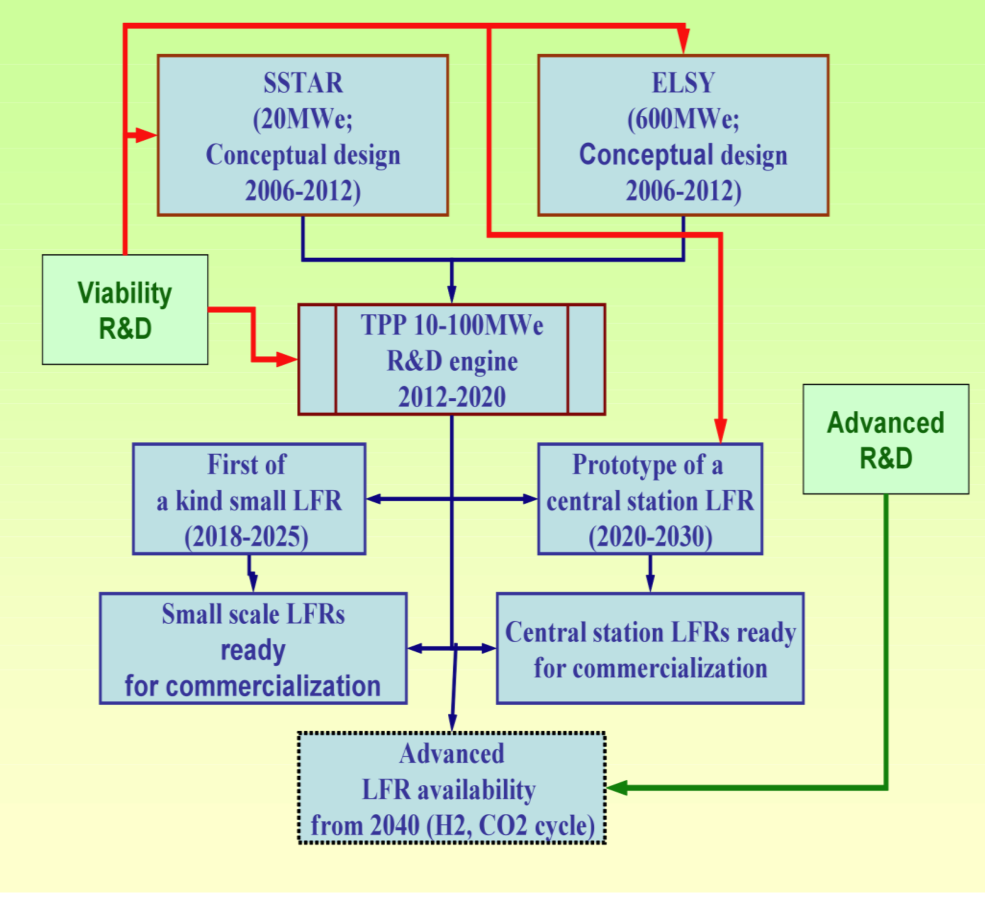
Generation IV International Forum

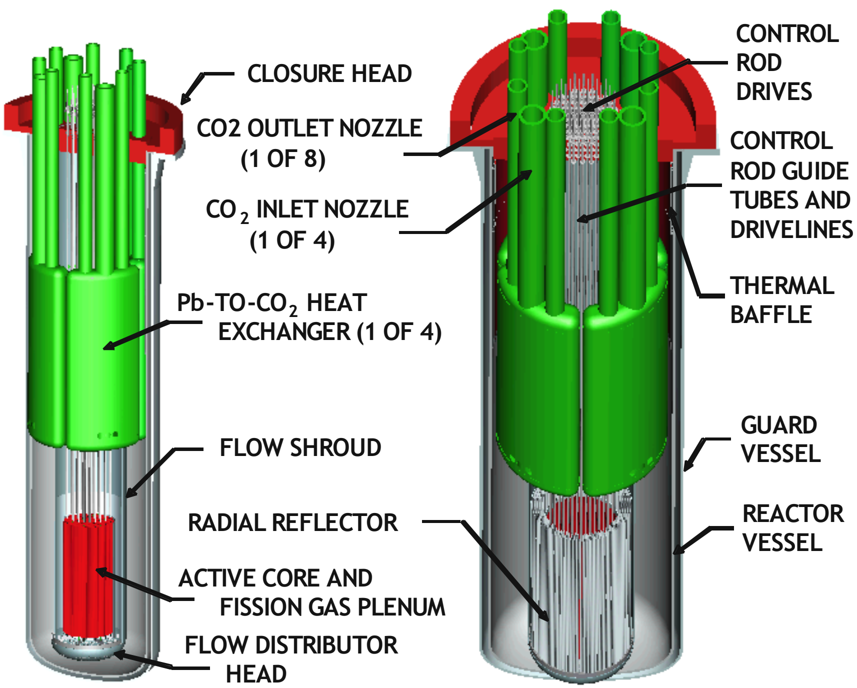
The GIF-LFR System Research Plan (SRP) recognizes two principal technology tracks:

- A small, transportable system of 10–100 MWe size that features a very long refueling interval. (SSTAR)

- A larger-sized system rated at about 600 MWe, intended for central station power generation and waste transmutation. (ELSY)



The Small Secure Transportable Autonomous Reactor (SSTAR)



SSTAR is a small natural circulation fast reactor of 20 MWe/45 MWt, that can be scaled up to 180 MWe/400 MWt.

The compact active core is removed by the supplier as a single cassette and replaced by a fresh core.

Key technical attributes include the use of lead (Pb) as coolant and a long-life sealed core in a small, modular system.

SSTAR Reactor Core Parameters

Coolant	Lead
Fuel	Transuranic Nitride, Enriched in N_{15}
Enrichment, %	5 Radial Zones, TRU/HM 1.7/3.5/ 17.2/19.0/20.7
Core Lifetime, years	30
Core Inlet/Outlet Temperature, ºC	420/567
Coolant circulation	Natural convection
Average (Peak) Discharge Burnup, MWd/Kg HM	81(131)

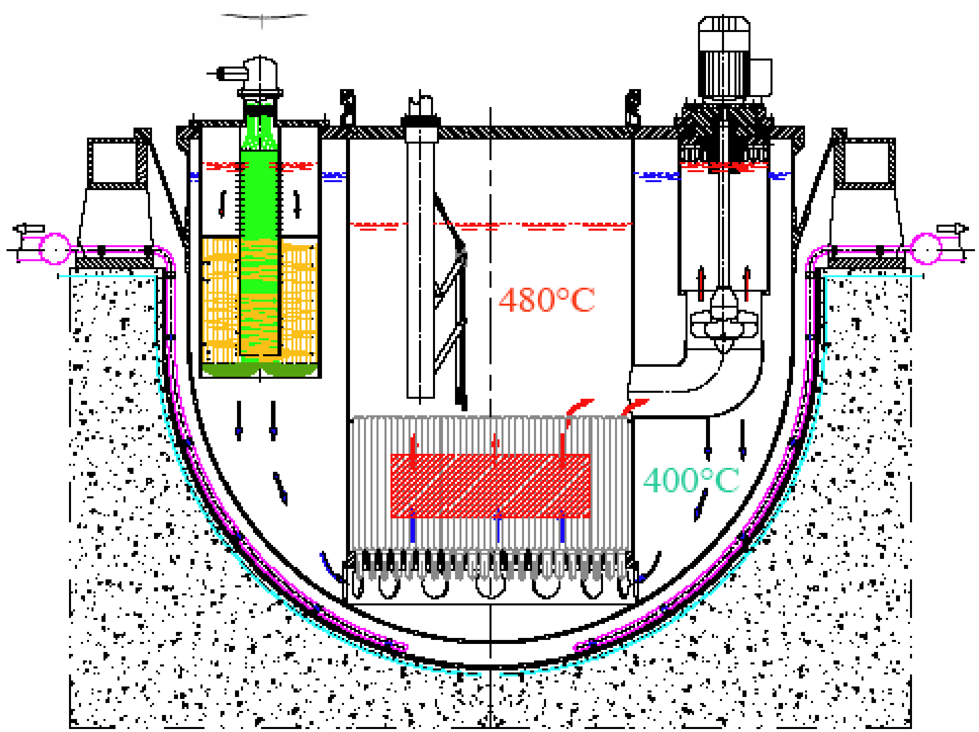
Peak Fuel Temperature, ºC	841
Peak Cladding Temperature, ºC	650
Fuel Pin Diameter, Cm	2.50
Fuel/Coolant Volume Fractions	0.45/0.35
Active Core Dimensions, Height/Diameter, m	0.976/1.22
Power conversion	S-CO_2 Brayton cycle

The SSTAR concept represents a novel approach to proliferation resistance

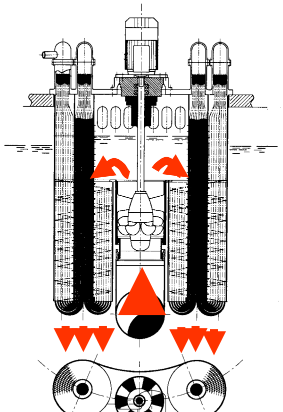
- **Sealed or cassette core: no on-site refueling by host**
- **Transportability: entire core and reactor vessel delivered as a unit**
- **Long-life Core: 30 year core life is a target**
- **Simple integrated controls: minimum operator intervention or maintenance required**
- **Local and remote observability**
- **Minimum industrial infrastructure required in host location**
- **Very small operational (and security) footprint**

ELSY (European Lead-colled System) is a 600 MWe LFR designed for central station operation

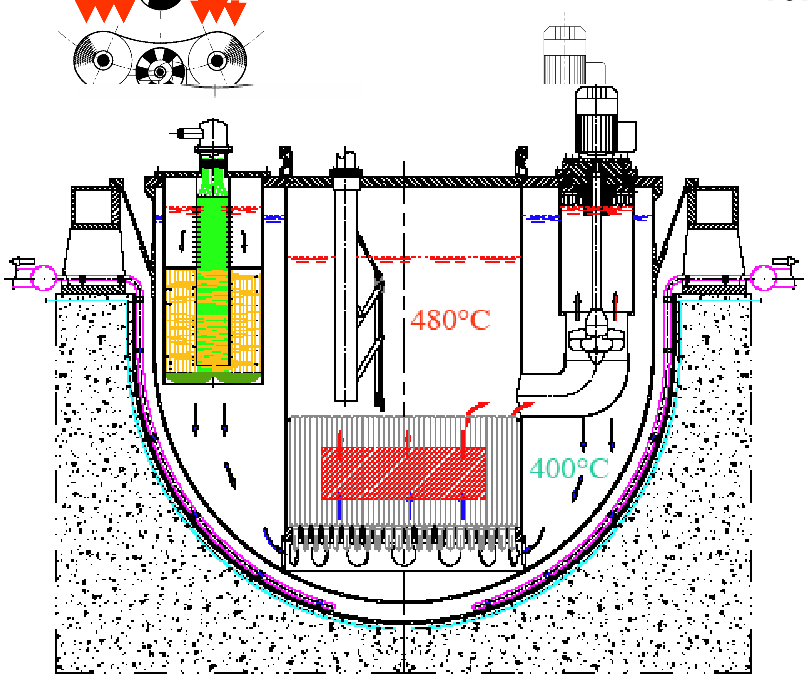
- ***Project funded at 7M Euro level, supported by EC and national programs***
- ***Pure Lead coolant***
- ***Forced cooling***
- ***Small temperature rise across the core***
- ***Integral steam generators and pumps***
- ***Substantial simplification in contrast with other LM reactors***

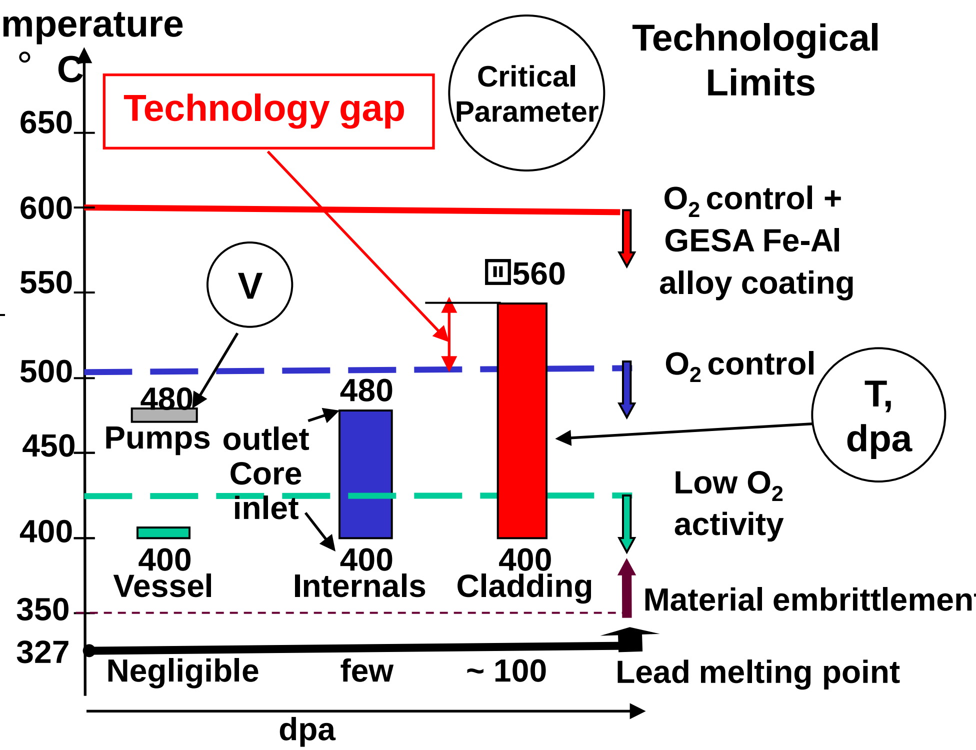


ELSY applies innovation in thermal cycle and materials to address corrosion issues



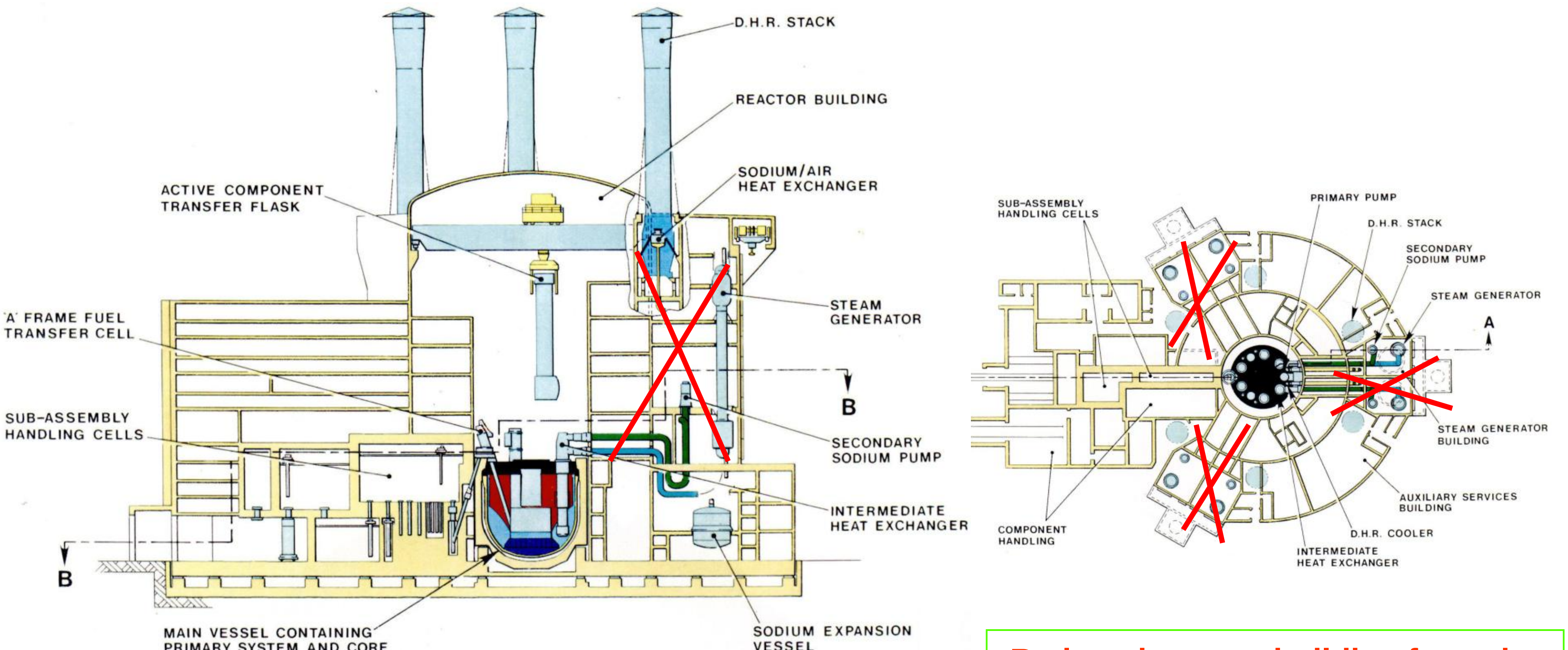
- ✓ Low-temperature thermal cycle to limit corrosion
- ✓ Use of aluminization of fuel cladding and SG tubes
- ✓ New material for pumps (MAXTHAL)





The elimination of the need for intermediate loops is the key for compactness of a LFR plant layout

No intermediate main loops, **(S. G. inside the reactor vessel)**



Reduced reactor building footprint

Reduced reactor building elevation

ELSY is an ongoing, rapidly developing program

- A key characteristic of ELSY is the simplicity and compactness of the primary system, all the in-vessel components being removable.

- New configurations, recently identified but not yet published appear to be very promising.

- Successful completion of the ELSY design may offer significant advances in compactness, simplification and ultimately overall economic performance

- Stay tuned for additional near-term results.

LFR Compliance with Generation IV Goals

Goal Areas	***Goals achievable*** **via *intrinsic coolant properties plus Engineering***
Sustainability	▪ ***Breeding gain close to 0*** ▪ ***Transmutation of MA***
Economics	▪ ***Simplicity*** ▪ ***Compactness***
Safety and Reliability	▪ ***Primary system at atmospheric pressure*** ▪ ***No risk of re-criticality in case of core melt*** ***(to be confirmed by severe accident analysis)***
Proliferation Resistance and Physical Protection	▪ ***Use of fuel containing MA*** ▪ ***Use of non-reactive coolant*** ▪ ***Sealed core and/or long refueling cycle***

SSTAR and ELSY operating parameters

	SSTAR	*ELSY*
Power	*20MWe/45MWth*	*600MWe/1500MWth*
Power conversion efficiencies	*44.2% (S-CO_2 Brayton cycle)*	*40% (steam cycle)*
Heat Removal	*Natural circulation*	*Forced cooling*
Decay Heat Removal	*Natural circulation*	*Natural circulation*
Fuel materials	*Nitride (of uranium or mixed actinides)*	*Oxide (of uranium or mixed actinides)*
Inlet/outlet temperatures, $^\circ$ C	*420/567*	*400/480*
Neutron spectrum	*Fast*	*Fast*

Some final comments

- Lead-cooled systems offer great promise for both central station and exportable (small) reactor missions
- International interest is strong and cooperation is essential
- Important research issues remain
- Some interesting topics for study might include:
  - Design of an early deployable (domestic SSTAR) small system
  - Evaluation of the flexibility range of fuel feeds in lead systems
  - Characteristics and designed of a combined technology pilot plant (“Demo”)
  - Evaluation of proliferation risk attributes of lead systems
  - Evaluation of long term radioactive waste residues from fuel and system activation

Any questions?